Atom Interferometry for Detection of Gravitational Waves

NIAC 2013 Spring Symposium
Chicago

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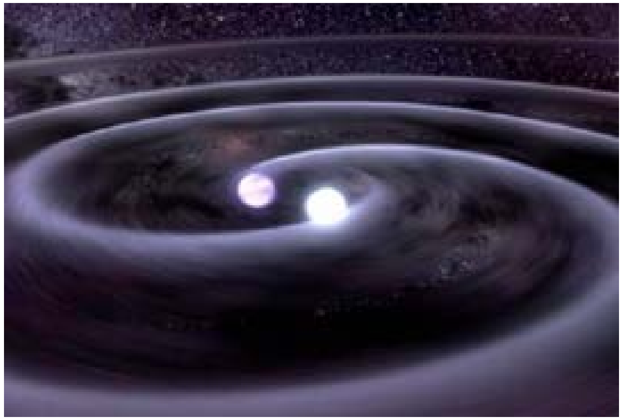
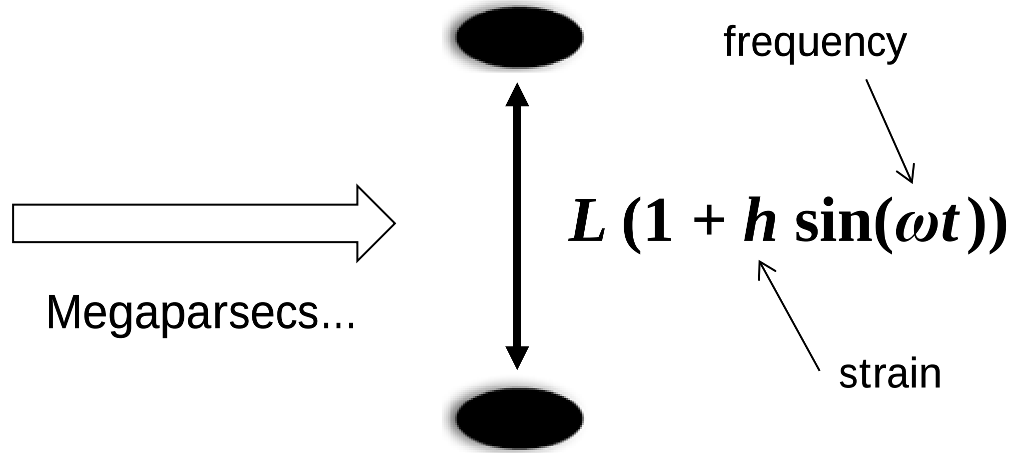
March 12, 2013

Gravitational Wave Detection





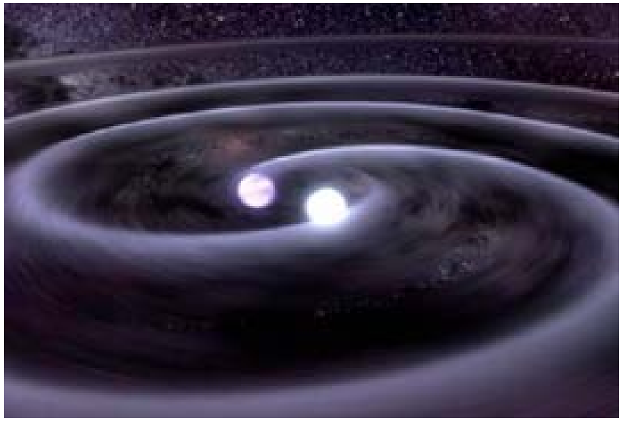
Why study gravitational waves?

- *New carrier for astronomy*: Generated by moving mass instead of electric charge
- *Tests of gravity*: Extreme systems (e.g., black hole binaries) test general relativity
- *Cosmology*: Can see to the earliest times in the universe

But, they are incredibly weak!

- Strain oscillation: Amplitude of motion depends on separation
- Example: 1000 km baseline, oscillation amplitude is **only 10 fm**

Gravitational Wave Detection



Why consider atoms?

- **Neutral** atoms are excellent “test particles” (follow geodesics)
- Atom interferometry provides **exquisite measurement** of geodesic
- **Single baseline** configuration possible (e.g., only two satellites)
- Same sensitivity as LISA, but **much smaller** (1000 x)
- Flexible operation modes (broadband, resonant detection)

Cold Atom Inertial Sensors

Cold atom sensors:

- Laser cooling; ~10^8 atoms, ~uK (no cryogenics)
- Advanced cooling techniques: ~nK or below
- Atom is freely falling (inertial test mass)
- Lasers measures motion of atom relative to sensor case
- Accelerometers, gravimeters, gyroscopes, gradiometers

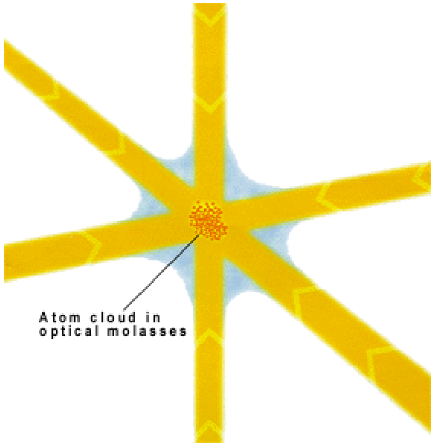
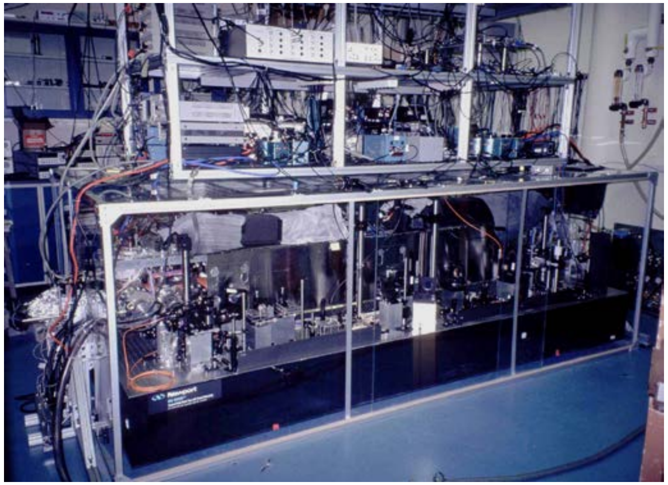
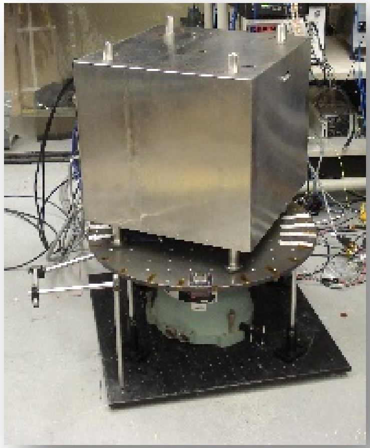


Image: http://www.nobelprize.org

Technology evolution:



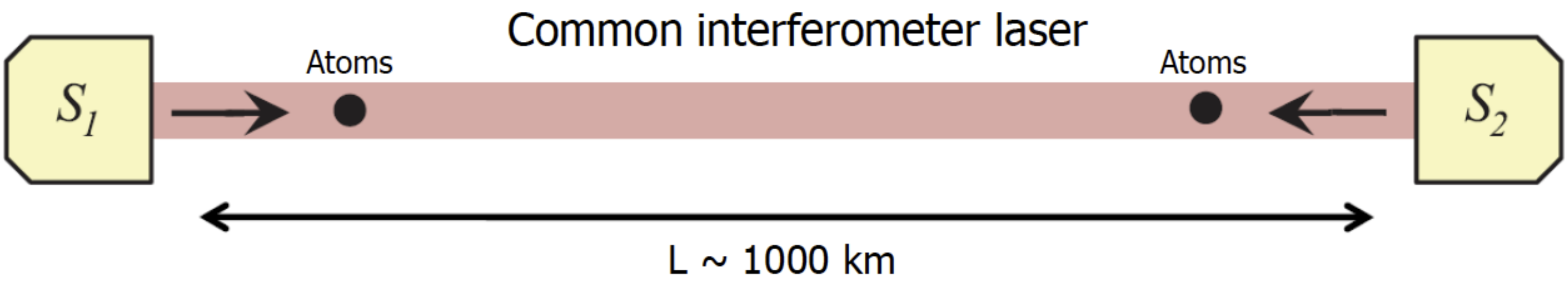
AI gyroscope (1997)

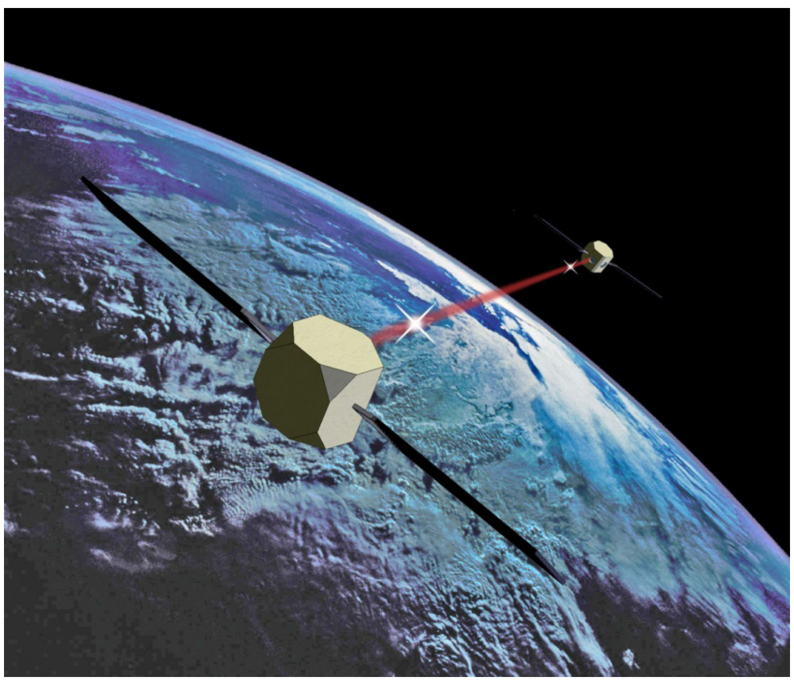


AI compact gyroscope (2008)

AOSense commercial AI gravimeter (2011)

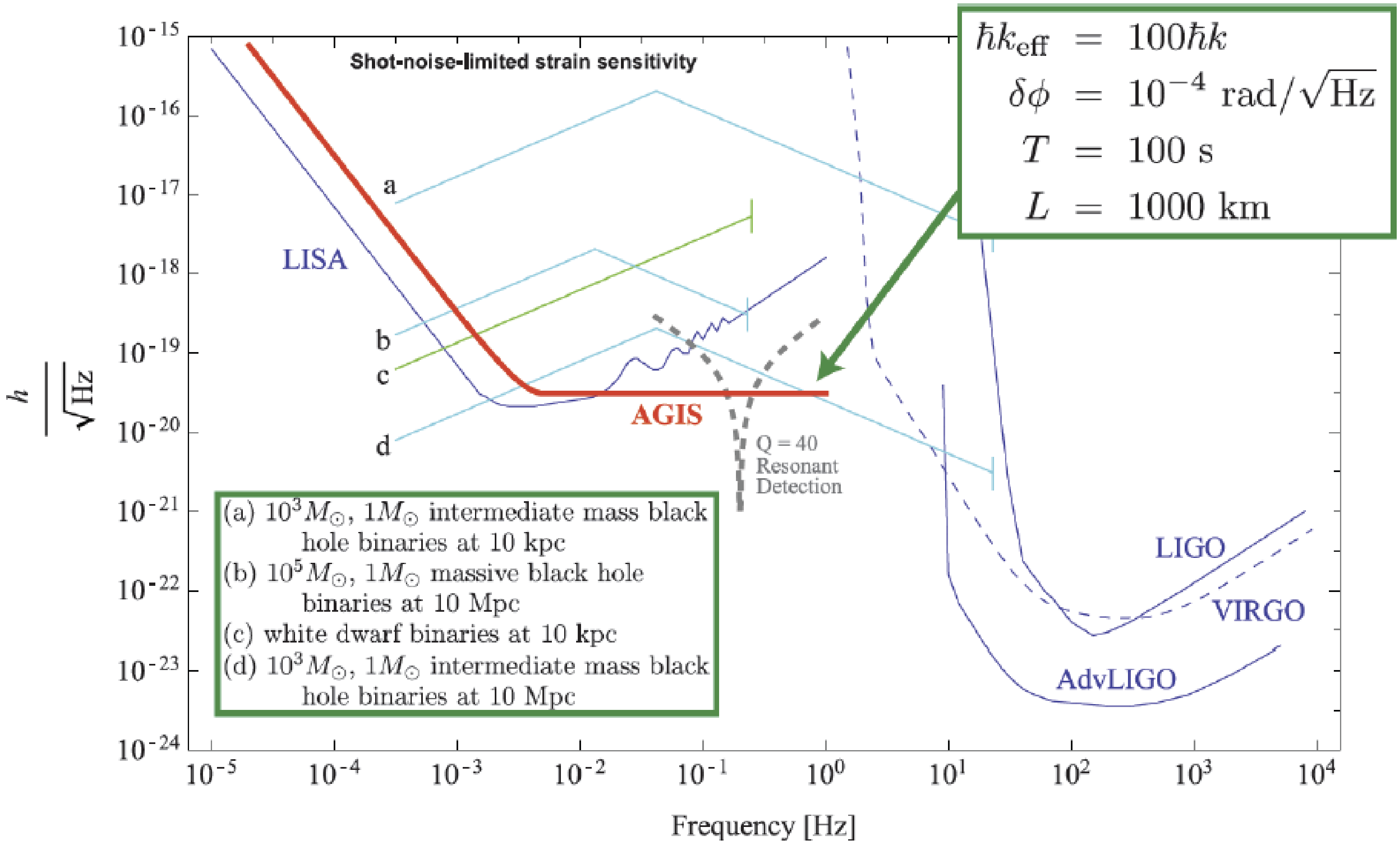
Satellite GW Antenna





- Atoms are test masses
- Atom is **inertially decoupled** (freely falling); insensitive to vibration
- *However*: Lasers vibrate, are noisy
- **Differential measurement** with common laser helps suppress noise

Strain Sensitivity



- Space-based atom GW detector could have science potential comparable to LISA
- Flexible atom optics allows for both “broadband” and “resonant” modes

Noise Model

Analysis to determine requirements on satellite jitter, laser pointing stability, atomic source stability, and orbit gravity gradients.

	Differential phase shift	Size (rad)	Constraint
1	$\frac{1485 k_{\rm eff}^3 \hbar^2}{4Lm^2} T^6 T_{\rm xx} \Omega_{\rm or} \delta\Omega$	$(180\ \mathrm{s})\delta\Omega$	$\delta\Omega < 0.57\ \mu\mathrm{rad/s}$
2	$\frac{1485 k_{\rm eff}^3 \hbar^2}{2Lm^2} T^6 \Omega_{\rm or}^3 \varepsilon_{zz} \delta\Omega$	$(350\ \mathrm{s})\varepsilon_{zz}\delta\Omega$	$\varepsilon_{zz} < 0.50$
3	$\frac{15}{2} k_{\rm eff} T^4 R \Omega_{\rm or}^2 \left(15T\left(T_{zz} + 3\Omega_{\rm or}^2\right) + 8\Phi\Omega_{\rm or}\right)\varepsilon_g \delta\Omega$	$(3\times 10^9\ \mathrm{s})\,\varepsilon_g\delta\Omega$	$\varepsilon_g < 5.8\times 10^{-8}$
4	$30 k_{\rm eff} T^4 \Omega_{\rm or}^4 \varepsilon_{\rm xx}(\delta x_{\rm n} - \delta x_{\rm f})$	$(22\ \mathrm{m}^{-1})\varepsilon_{\rm xx}(\delta x_{\rm n} - \delta x_{\rm f})$	$(\delta x_{\rm n} - \delta x_{\rm f})\varepsilon_{\rm xx} < 4.5\ \mu\mathrm{m}$
5	$15 k_{\rm eff} T^4 T_{\rm xx} \Omega_{\rm or}\left(\frac{k_{\rm eff}\hbar}{Lm} + 9T\Omega_{\rm or}^2\right)(\delta z_{\rm f} - \delta z_{\rm n})$	$(0.84\ \mathrm{m}^{-1})(\delta z_{\rm f} - \delta z_{\rm n})$	$(\delta z_{\rm f} - \delta z_{\rm n}) < 120\ \mu\mathrm{m}$
6	$30 k_{\rm eff} T^4 \Omega_{\rm or}^3\left(\frac{k_{\rm eff}\hbar}{Lm} + 9T\Omega_{\rm or}^2\right)\varepsilon_{zz}(\delta z_{\rm f} - \delta z_{\rm n})$	$(1.7\ \mathrm{m}^{-1})\varepsilon_{zz}(\delta z_{\rm f} - \delta z_{\rm n})$	$\varepsilon_{zz} < 0.49$
7	$\frac{45}{2} k_{\rm eff} T^5\left(T_{\rm xx}^2 + 6T_{\rm xx}\Omega_{\rm or}^2 + 4T_{zz}\Omega_{\rm or}^2 + 5\Omega_{\rm or}^4\right)\Delta v_x$	$(270\ \mathrm{s/m})\Delta v_x$	$\Delta v_x < 370\ \mathrm{nm/s}$
8	$3 k_{\rm eff} T^4 \Omega_{\rm or}\left(\frac{9k_{\rm eff}^2\hbar^2}{L^2m^2} - 5T_{\rm xx}\right)\Delta v_z$	$(9.6\times 10^3\ \mathrm{s/m})\,\Delta v_z$	$\Delta v_z < 10\ \mathrm{nm/s}$
9	$30 k_{\rm eff} T^4 \varepsilon_{zz}\Omega_{\rm or}^3 \Delta v_z$	$(1.9\times 10^4\ \mathrm{s/m})\,\varepsilon_{zz}\Delta v_z$	$\varepsilon_{zz} < 0.52$
10	$60\frac{\hbar k_{\rm eff}^2}{L^2 m} T^4 T_{\rm yy}\delta v_{\rm yn}\delta y_{\rm n}$	$(4.3\times 10^{-2}\ \mathrm{s/m^2})\,\delta v_{\rm yn}\delta y_{\rm n}$	$\delta v_{\rm yn}\delta y_{\rm n} < 23\ \mathrm{cm^2/s}$
11	$36 k_{\rm eff}^3 \frac{\hbar^2}{Lm^2}\Omega_{\rm or} T^3 (7 + 8\cos(\omega T))\sin^4\left(\frac{\omega T}{2}\right)\overline{\delta\theta}$	$(3.9\times 10^5)\,\overline{\delta\theta}$	$\overline{\delta\theta} < 0.26\ \mathrm{nrad}$
12	$4 k_{\rm eff}\delta z_n (7 + 8\cos(\omega T))\sin^4\left(\frac{\omega T}{2}\right)\overline{\delta\theta}$	$(1.3\times 10^{10}\ \mathrm{m}^{-1})\,\delta z_n\overline{\delta\theta}$	$\overline{\delta\theta} < 0.77\ \mathrm{nrad}$
13	$\frac{27\sqrt{2}}{4} k_{\rm eff} x_n \frac{L}{R}\Omega_{\rm or}^2 T^2 \chi(\omega T)\overline{\delta\theta}$	$(1.1\times 10^4)\,x_n\overline{\delta\theta}$	$\overline{\delta\theta} < 0.91\ \mathrm{nrad}$

J. Hogan et al., GRG **43**, 7 (2011).

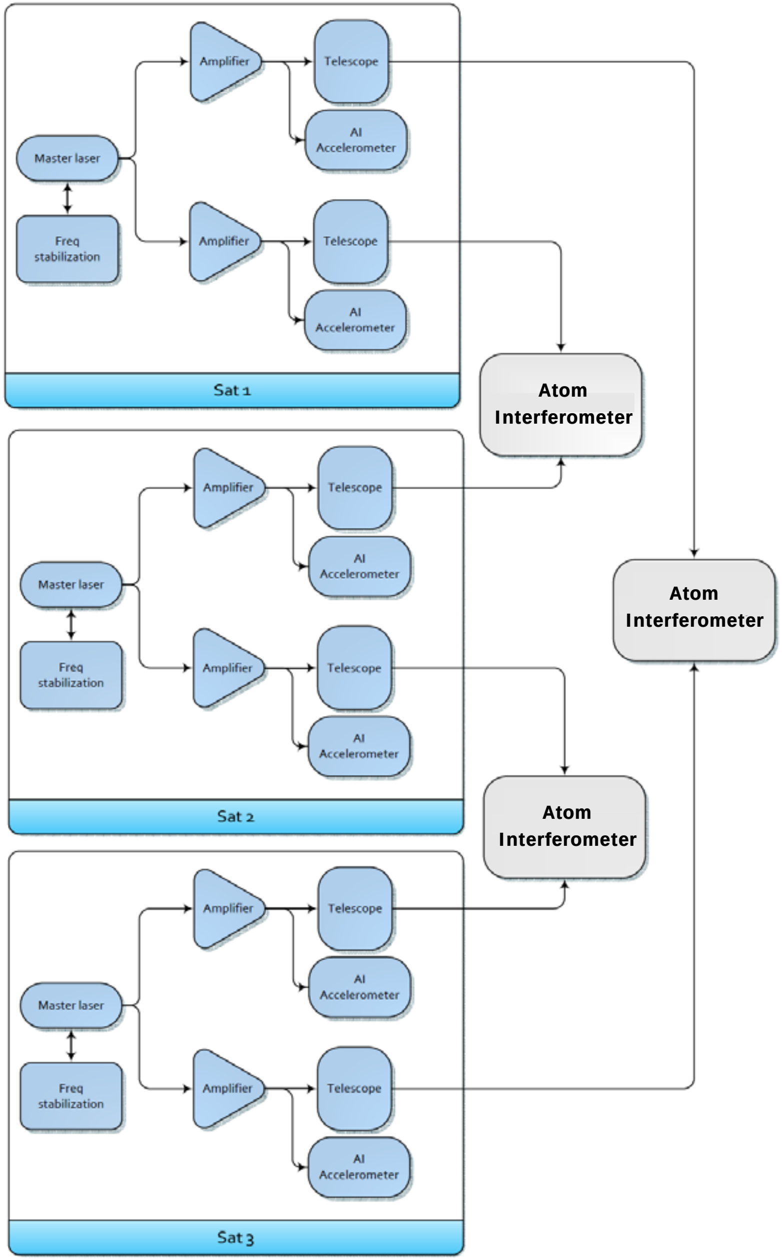
System architectures under analysis

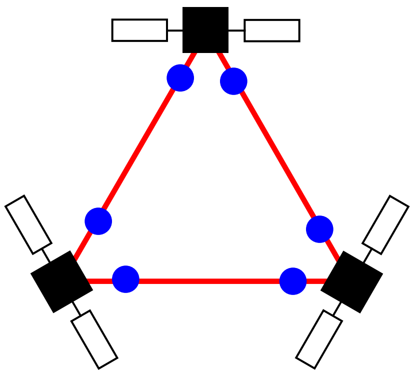
Currently evaluating several architectures:

1) Three satellite, **Rb**
2) Two satellite, **Rb** + atomic phase reference
3) Two satellite, **Sr**, single photon transition

Top level trade space is driven by strategy employed to **mitigate laser frequency noise**, which, if uncontrolled, can mask GW signatures.

3 Satellite Rb



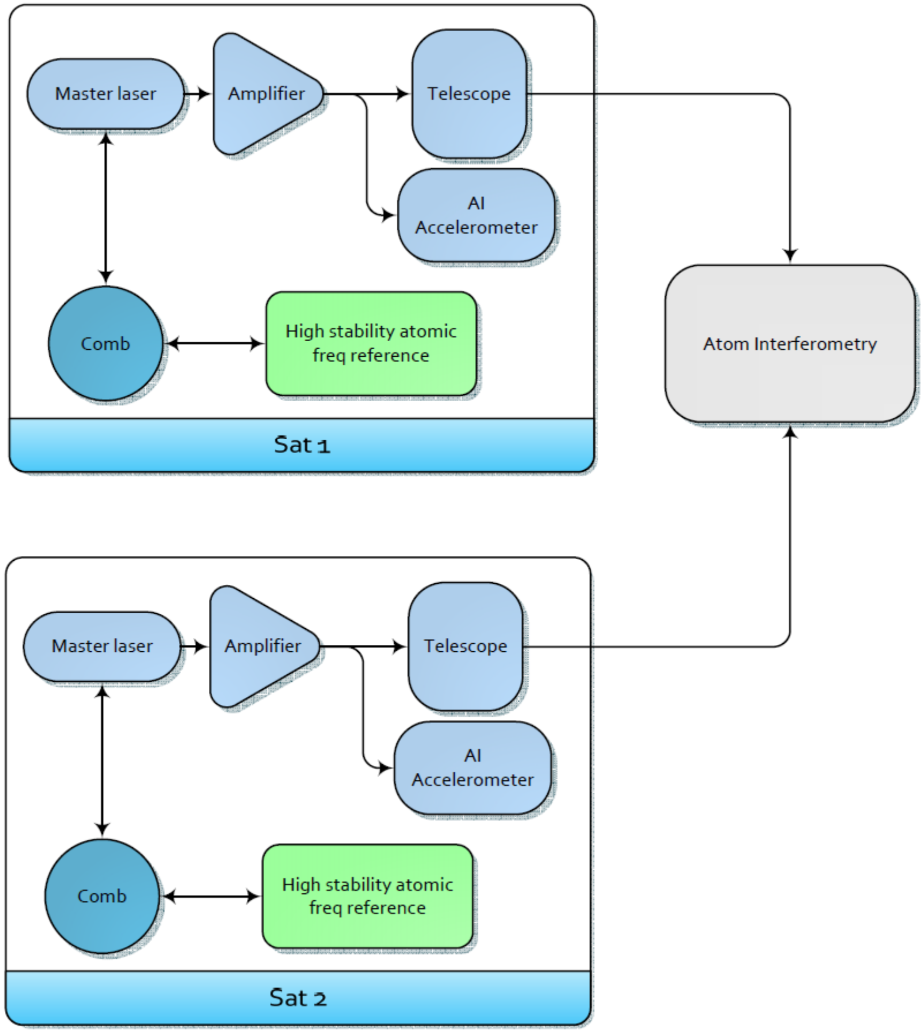


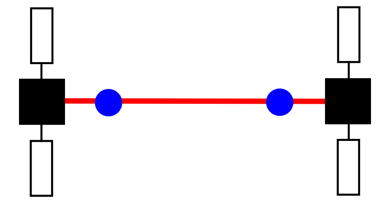
- Conventional, proven atom optics (Rb atom)

- Three satellites allow TDI for compensation of laser frequency noise.

- AI accelerometers to measure satellite vibration noise, which leads to laser frequency noise due to the Doppler effect.

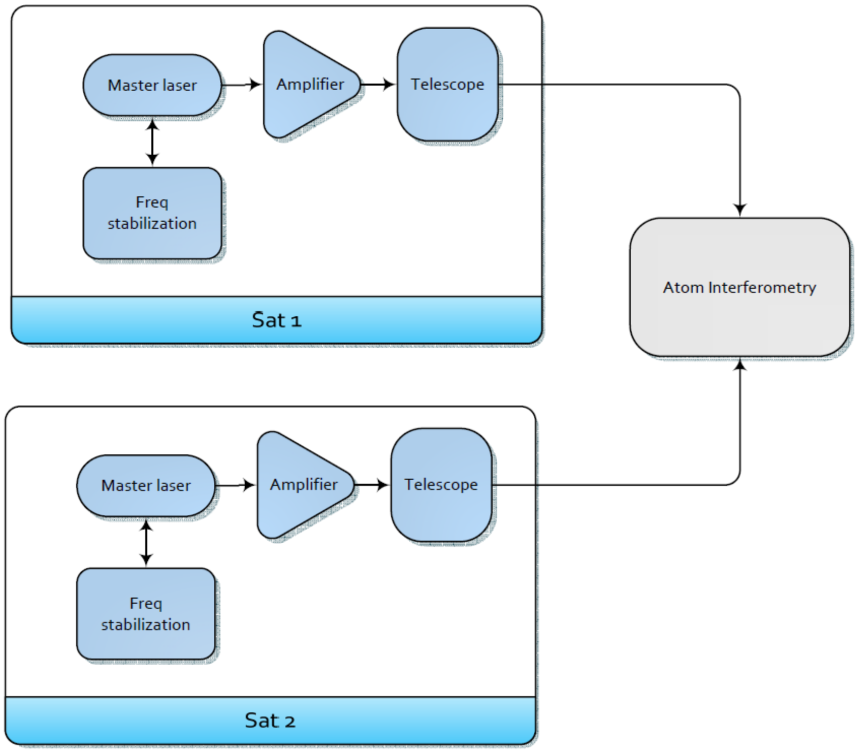
2 Satellite Rb + Atomic Reference

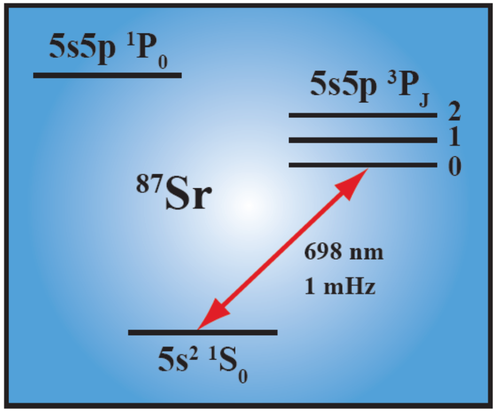




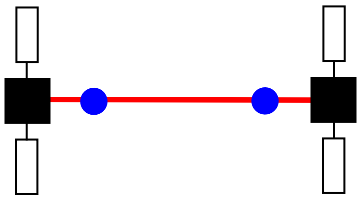
- Conventional, proven atom optics (Rb atom)
- Single baseline (two satellites)
- Atomic frequency reference (e.g.,Sr) for laser noise tracking
- AI accelerometers to measure satellite vibration noise

2 Satellite Sr Single Photon





Clock transition in candidate atom ^{87}Sr



- Single baseline (two satellites)
- Single photon atom optics (e.g., Sr) for laserand satellite acceleration noise immunity
- Atoms act as clocks, measuring the light travel time across the baseline

Requirements

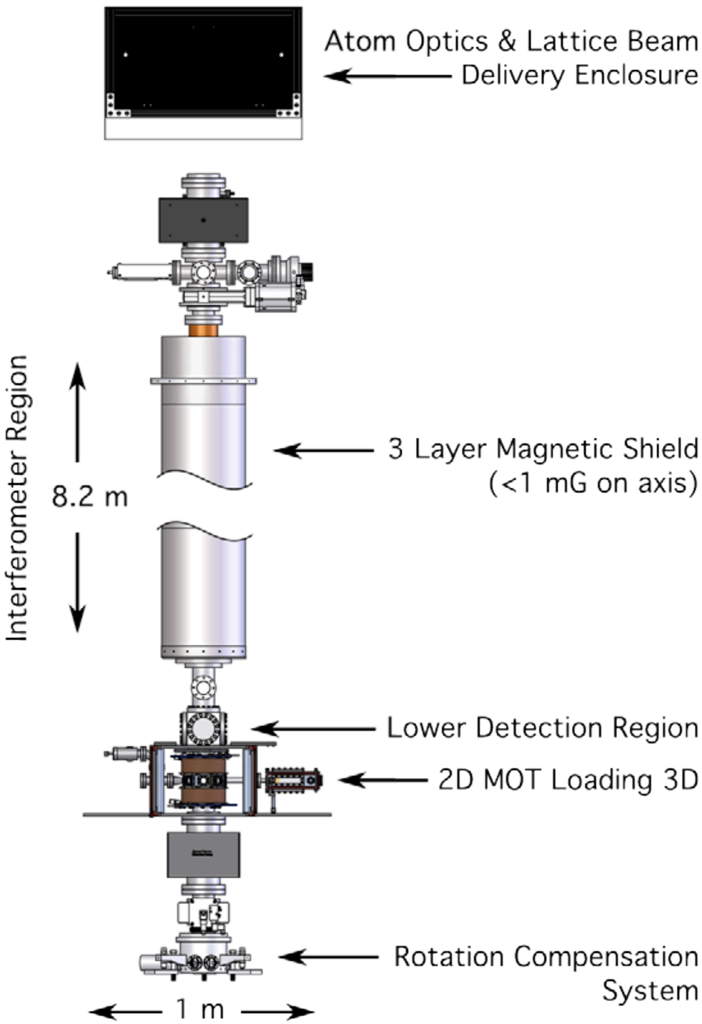
	Rb Triangle	Rb Single Arm	Sr Single Arm
Sat. acceleration noise (longitudinal)	AI accelerometer; 10^{-13} g/Hz$^{1/2}$	AI accelerometer; 10^{-13} g/Hz$^{1/2}$	10^{-8} g/Hz$^{1/2}$
Transverse position jitter	10 nm/Hz$^{1/2}$	10 nm/Hz$^{1/2}$	10 nm/Hz$^{1/2}$
Spatial wavefront	Lambda/100	Lambda/100	Lambda/100
Atom cloud temperature	100 pK	100 pK	1 pK
Pointing stability	0.1 μrad	0.1 μrad	0.1 μrad
Magnetic fields	0.1 nT/Hz$^{1/2}$	0.1 nT/Hz$^{1/2}$	4 nT/Hz$^{1/2}$
Laser phase noise	10 kHz/Hz$^{1/2}$ (TDI)	Atomic phase reference	10 Hz linewidth; 100 kHz/Hz$^{1/2}$
Atom optics	100 $\hbar k$	100 $\hbar k$	100 $\hbar k$
Formation flying	3 satellites	2 satellites	2 satellites
Atom source	10^8/s Rb	10^8/s Rb	10^8/s Sr

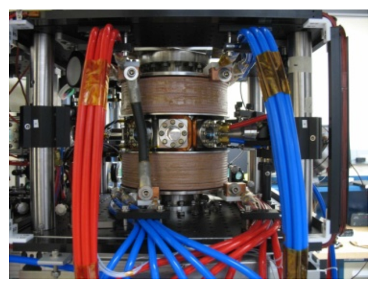
Atom Technology Roadmap

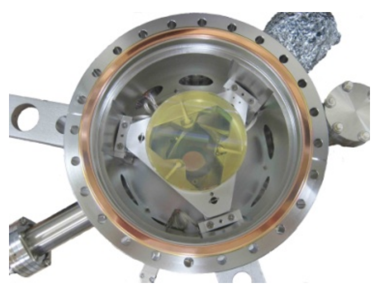
- Large wavepacket separation
- Large Momentum Transfer (LMT) atom optics
- Ultracold atoms temperature
- Optical wavefront noise mitigation
- Phase readout
- Satellite rotation jitter mitigation
- Strontium atom interferometry development

Can address much of the risk on ground

Ground-based proof-of-concept



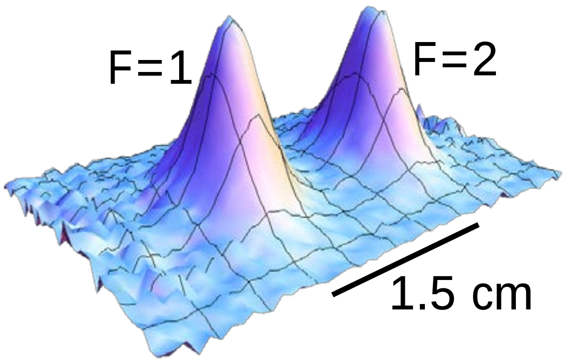


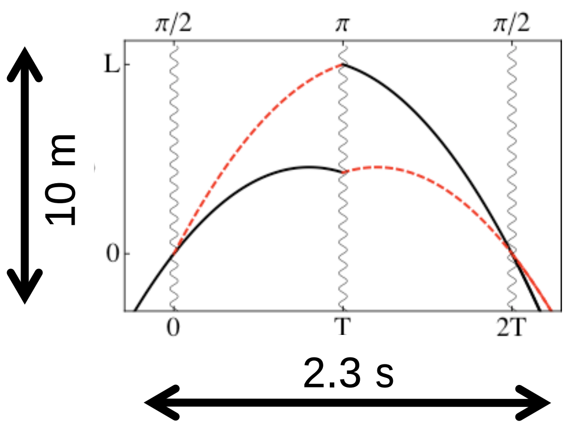


- Ultracold atom source
  - >10^6 at 50 nK
- Optical Lattice Launch
  - 13.1 m/s with 2372 photon recoils to 9 m
- Atom Interferometry
  - 2 cm $1/e^2$ radial waist
  - 500 mW total power
  - Dyanmic nrad control of laser angle with precision piezo-actuated stage
- Detection
  - Spatially-resolved fluorescence imaging
  - Two CCD cameras on perpendicular lines of sight

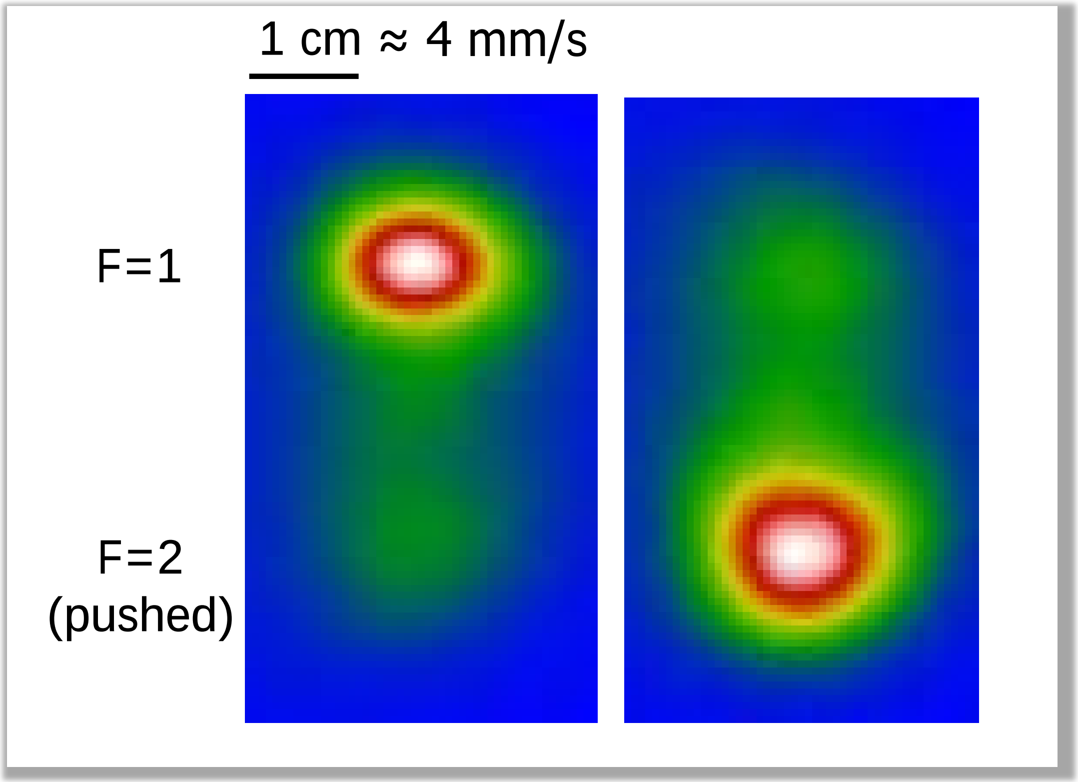
Atom Interferometry Results

t = T: Image at apex





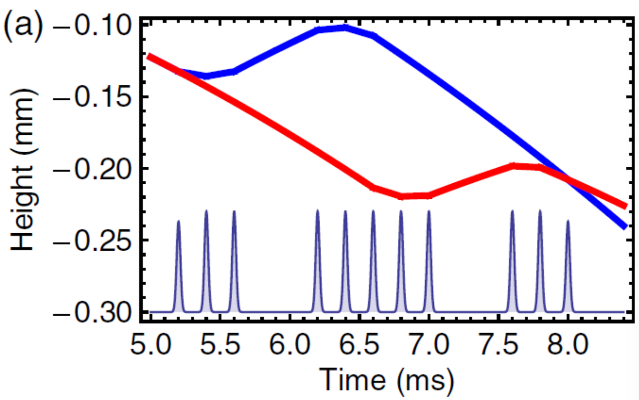
Images of Interferometry

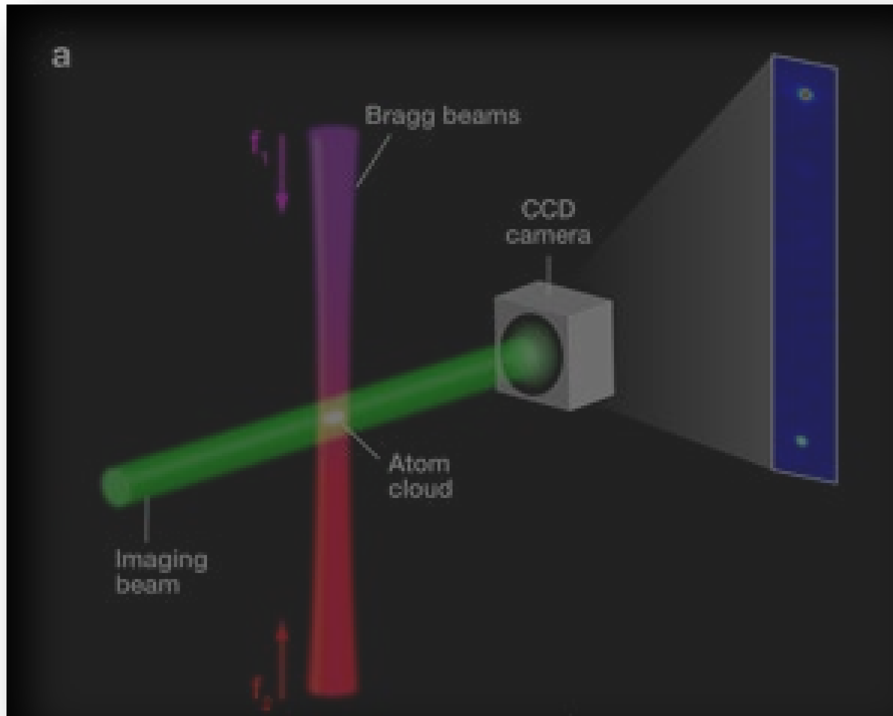


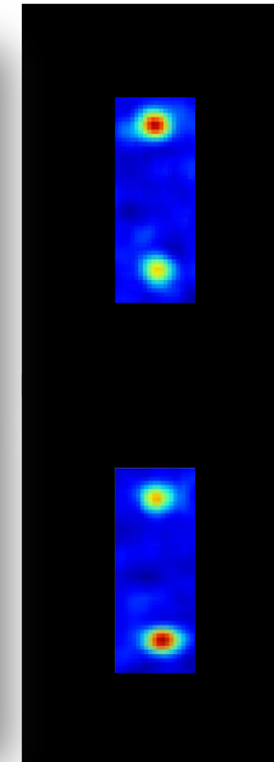
Record phase: $\Delta\phi = k_{\mathrm{eff}} g T^2 \approx 2 \times 10^8 \,\mathrm{rad}$

Record duration: $2T = 2.3$ s

LMT Atom Interferometry







102 photon recoil atom optics

High contrast

0.6 m/s recoil

Chiow, PRL, 2011

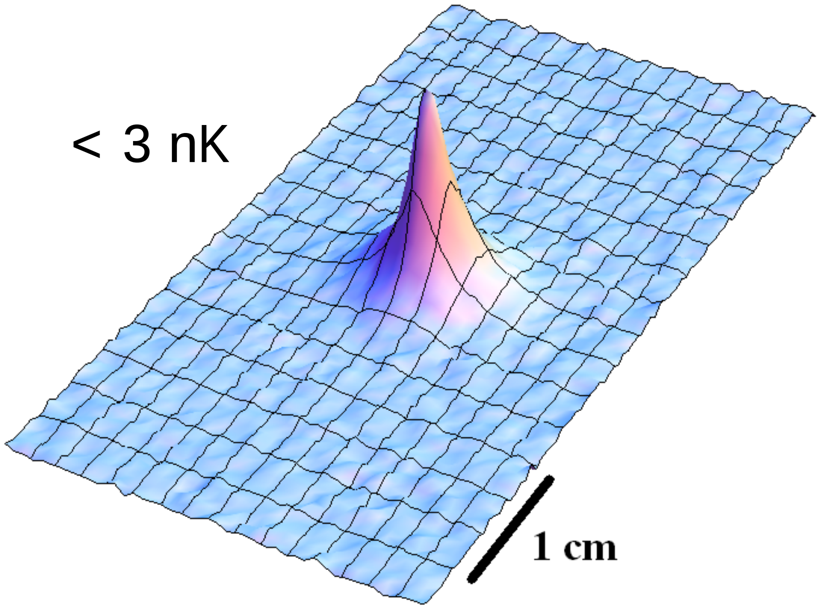
Coming Next: LMT atom optics in the 10 m tower

~1 m wavepacket separation

7 x 10^{-14} g / shot

Magnetic Lens Cooling Results

- Low temperatures (< nK) are required for Sr and Rb
- Conventional cooling procedure yields < μK
- Use a magnetic "lens" to reduce ensemble thermal energy further

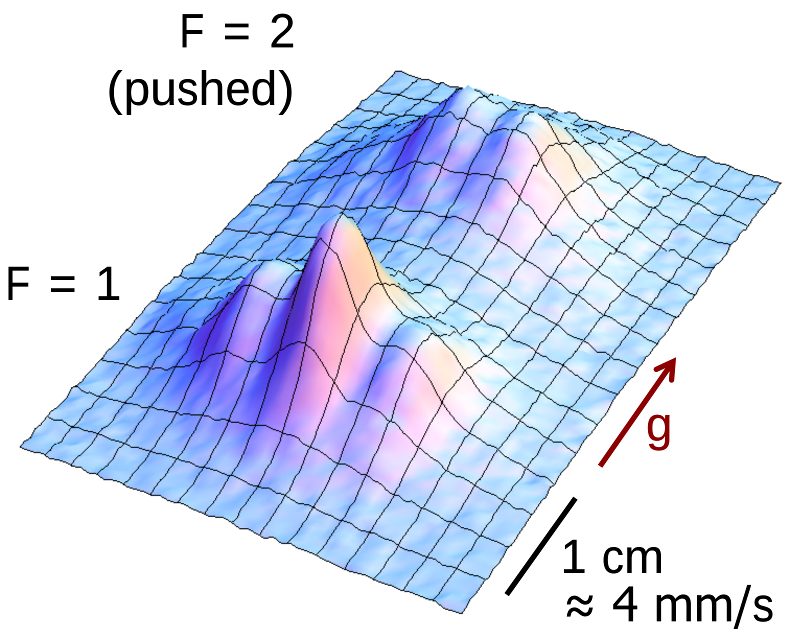


Atom cloud imaged after 2.6 seconds free-fall.

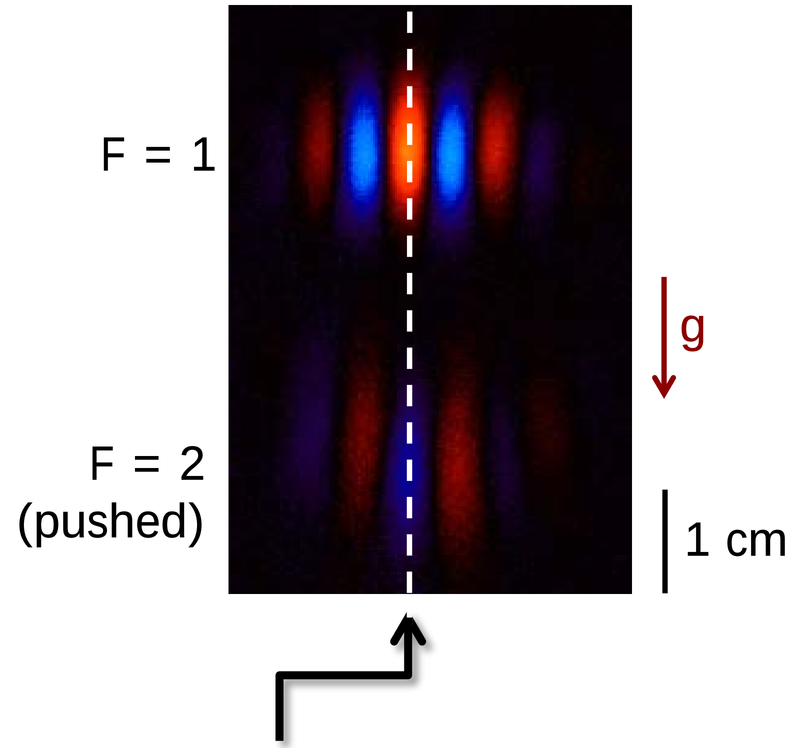
→ Successful proof-of-principle demonstration
→ Cooling performance limited by Earth gravity
→ Picokelvin range possible in space

Phase Shear Readout

- Direct imaging of spatial distribution
- Phase shear (fringes) applied by tilting laser



Phase Shear Readout (PSR)



Single-shot interferometer phase measurement

Mitigates several noise sources:

✓ Satellite pointing jitter and residual rotation readout

✓ Laser wavefront aberration *in situ* characterization

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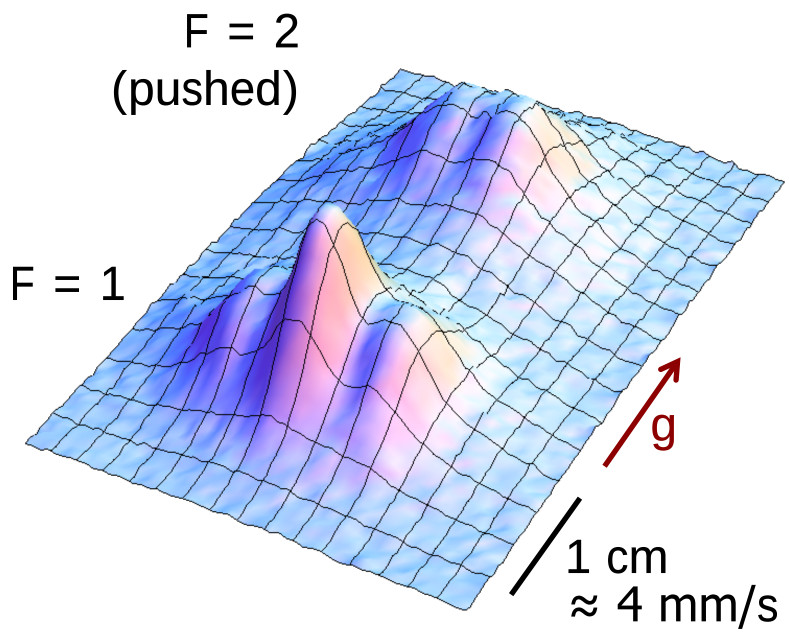

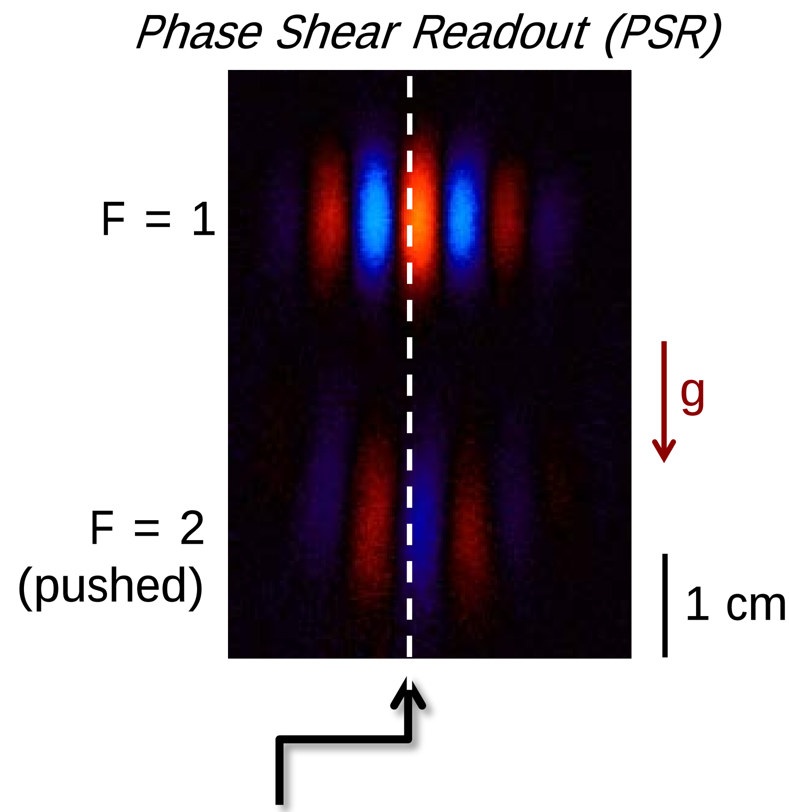

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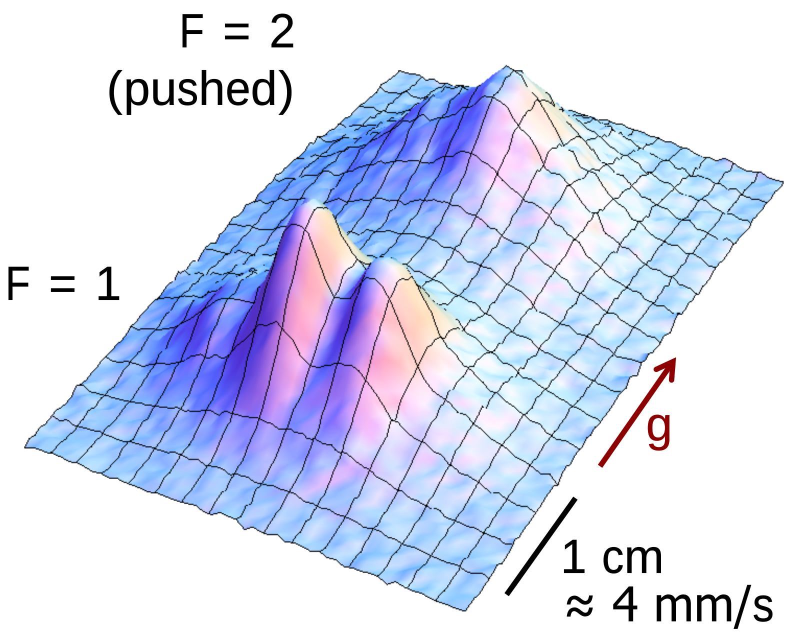

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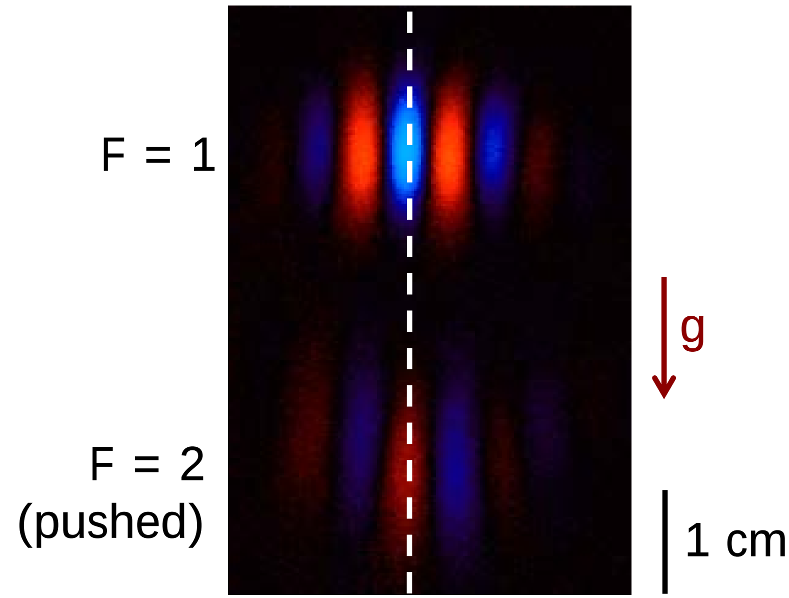

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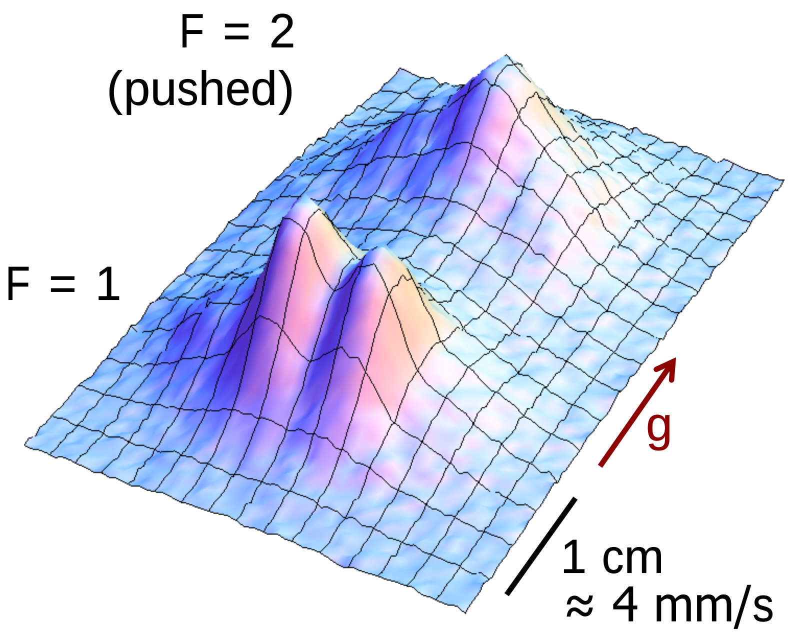

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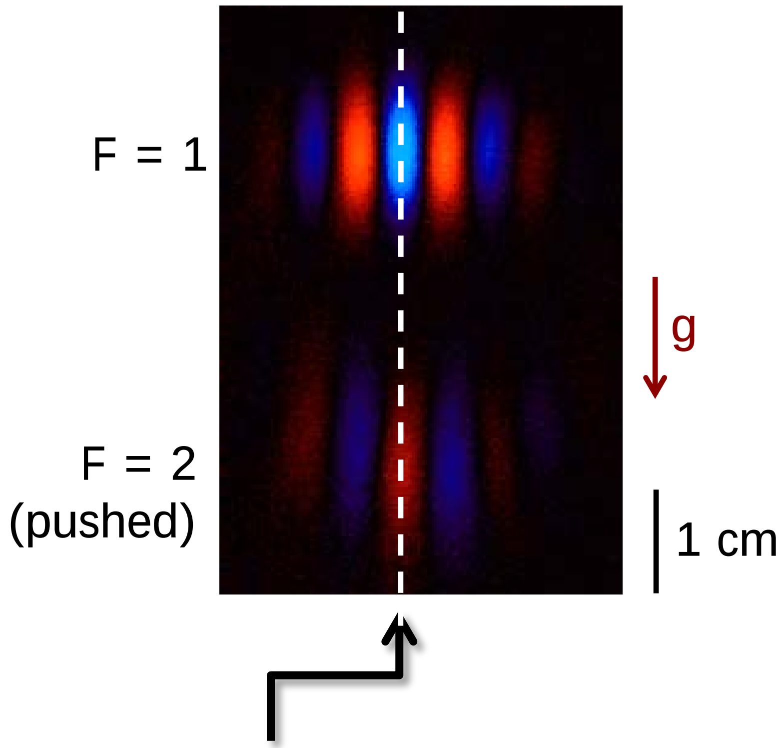

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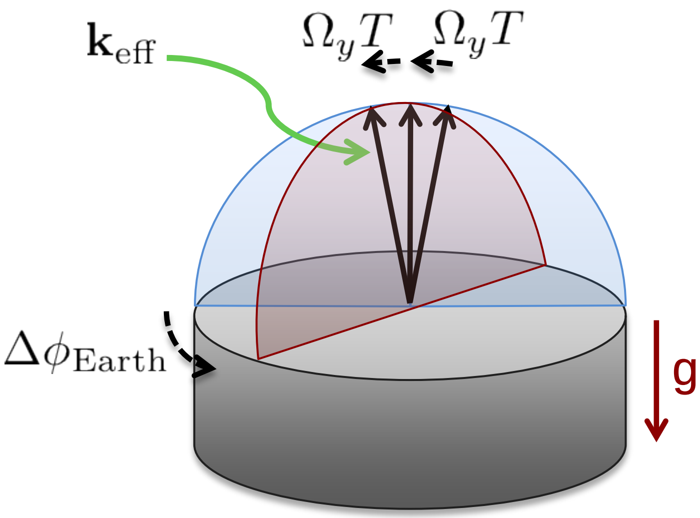
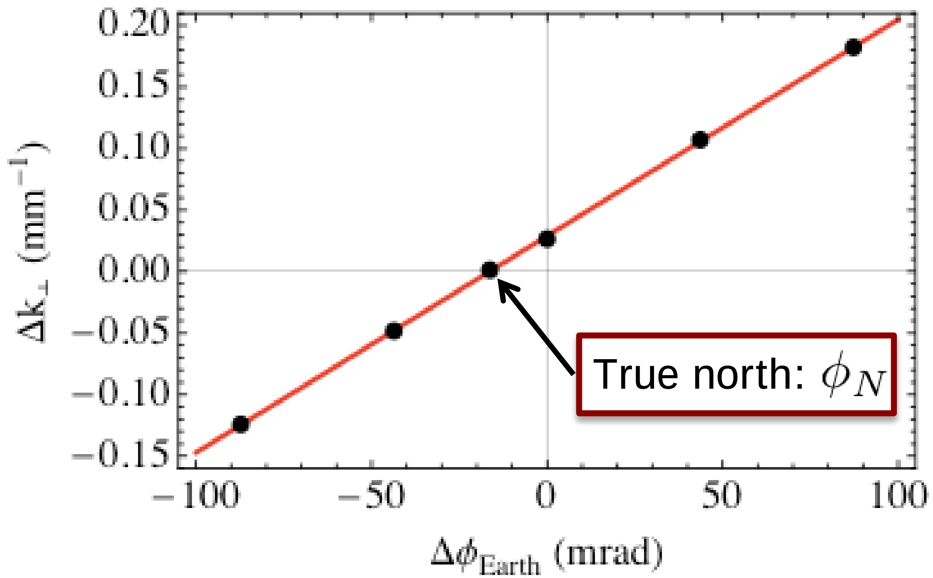
✓ Laser wavefront aberration *in situ* characterization

Application: Terrestrial Gyrocompass



Precision: 20 mdeg
Repeatability: ~ 1 mdeg
Correction to axis: -0.93 deg

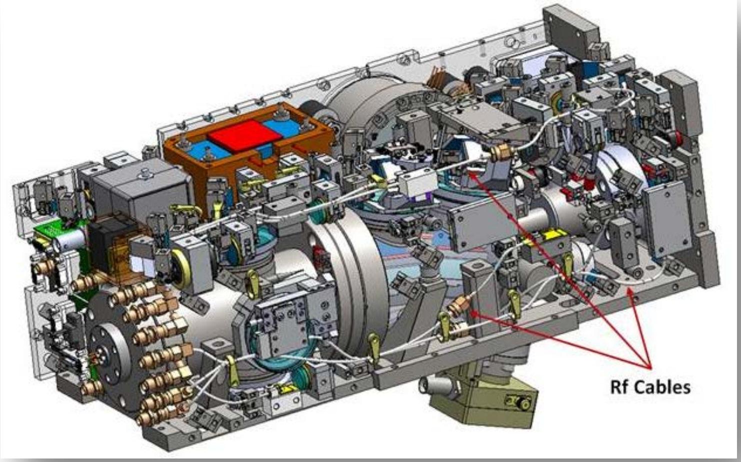


Must find the correct **plane of rotation**

Beam Angle + Coriolis Error:

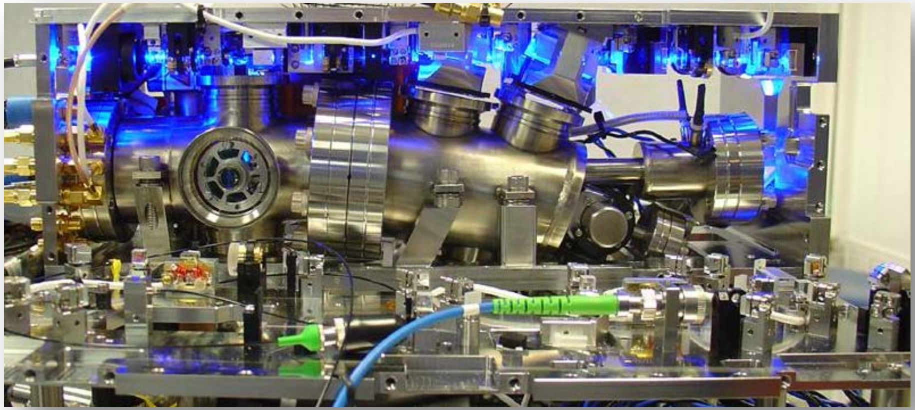
$$\Delta\phi_\perp = k_{\text{eff}}\theta_3 x_3 + 2k_{\text{eff}} v_x T^2 \Omega_y \sin(\Delta\phi_{\text{Earth}} - \phi_{\text{N}})$$

DARPA QuASAR SBOC-1/Optical clock



6 liter physics package.

Contains all lasers, Sr source, 2D MOT, Zeeman slower, spectrometer, pumps, and 3 W Sr oven.

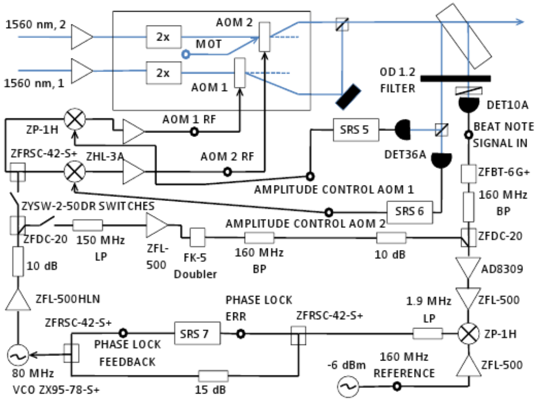


As built view with front panel removed in order to view interior.

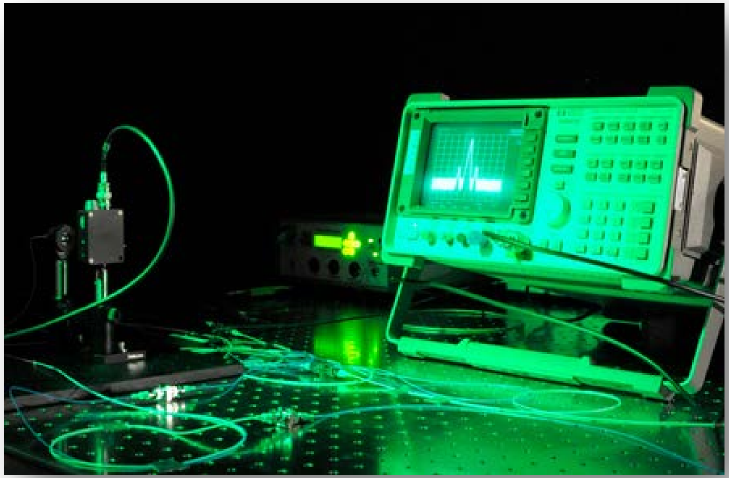
Stanford/GSFC High Power Laser Development

Stanford atom optics laser system.

GSFC and Stanford have pursued collaborative development of high power laser systems for atom interferometry.



Stanford laser control schematic



GSFC high power laser. GSFC will characterize laser wavefront and is developing a cavity enhanced system.

STANFORD UNIVERSITY

Atom Technology Progress

- Large wavepacket separation
- ✓ Large Momentum Transfer (LMT) atom optics
- ✓ Ultracold atoms temperature
- Optical wavefront noise mitigation
- ✓ Phase readout
- ✓ Satellite rotation jitter mitigation
- ✓ Strontium atom interferometry development

Phase II Objectives

Experimentally demonstrate GW detection protocols (Stanford)

Develop detailed system architecture, design, and error analysis (GSFC and Stanford)

Collaborators

Stanford University

PI:

Mark Kasevich

EP:

Susannah Dickerson
Alex Sugarbaker

LMT:

Sheng-wey Chiow
Tim Kovachy

Theory:

Peter Graham
Savas Dimopoulos
Surjeet Rajendran

Former members:

David Johnson (Draper)
Jan Rudolf (Rasel Group)

Also:

Philippe Bouyer (CNRS)

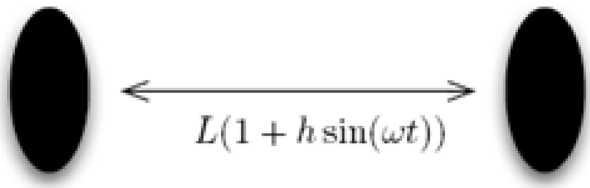
NASA Goddard Space Flight Center

Babak Saif
Bernard D. Seery
Lee Feinberg
Ritva Keski-Kuha

AOSense

Extra

Gravitational Wave Phase Shift Signal



$$ds^2 = dt^2 - (1 + h\sin(\omega(t-z)))dx^2 - (1 - h\sin(\omega(t-z)))dy^2 - dz^2$$

Laser ranging an atom (or mirror) that is a distance *L* away:

Position $\longrightarrow$ $x \sim L(1 + h\sin(\omega t))$

Acceleration $\longrightarrow$ $a \sim hL\omega^2 \sin(\omega t)$

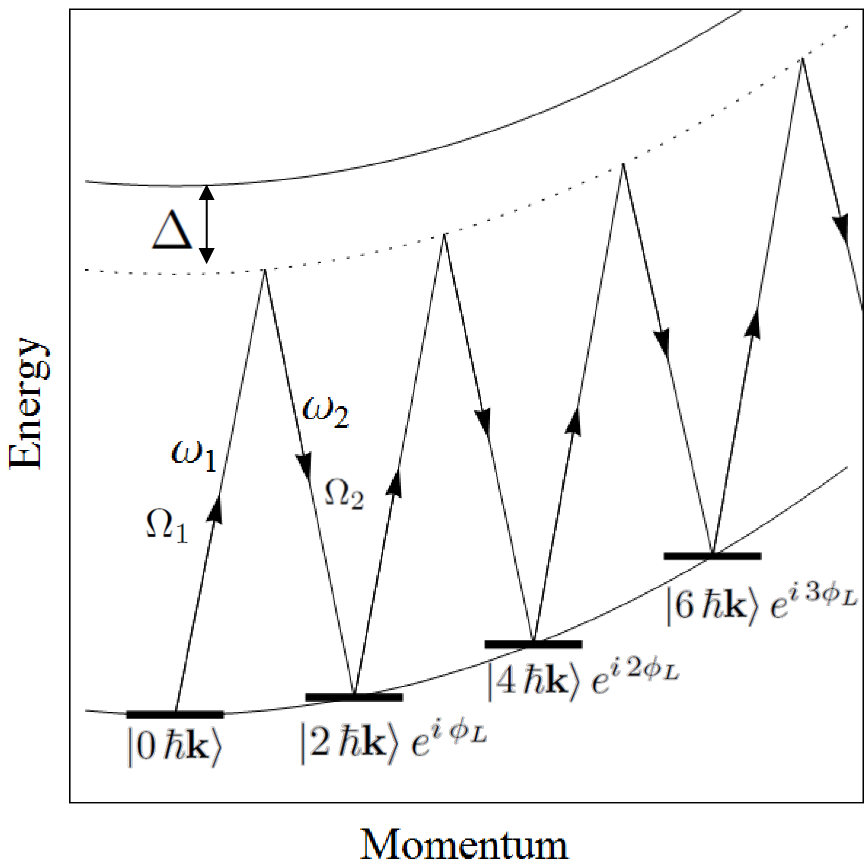
Phase Shift: $$\boxed{\Delta\phi = kaT^2 \sim khL\omega^2 \sin(\omega t)T^2}$$

Relativistic Calculation: $$\Delta\phi_{\text{tot}} = 2hk_{\text{eff}} \sin^2\left(\frac{\omega T}{2}\right)\frac{\sin(\omega L)}{\omega}\sin(\omega t)$$

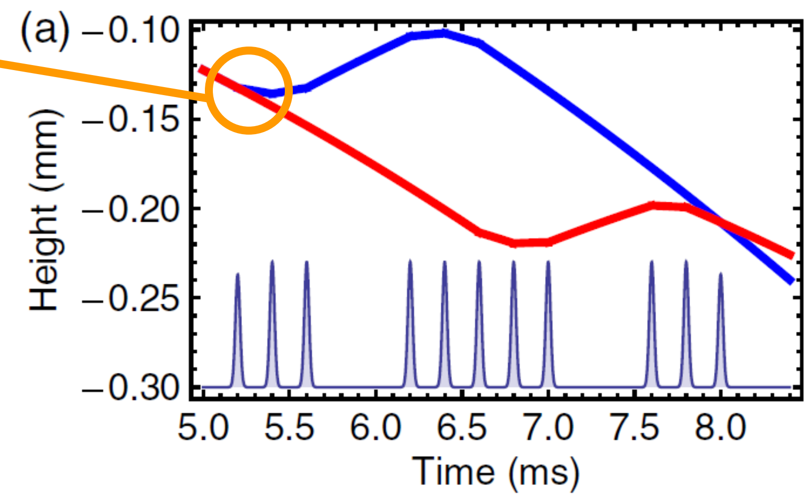
LMT Beamsplitters: Coherent Phase Amplification

- Large momentum transfer (LMT) beamsplitters – multiple laser interactions
- Each laser interaction adds a **momentum recoil** and imprints the **laser's phase**

LMT energy level diagram



Example LMT interferometer

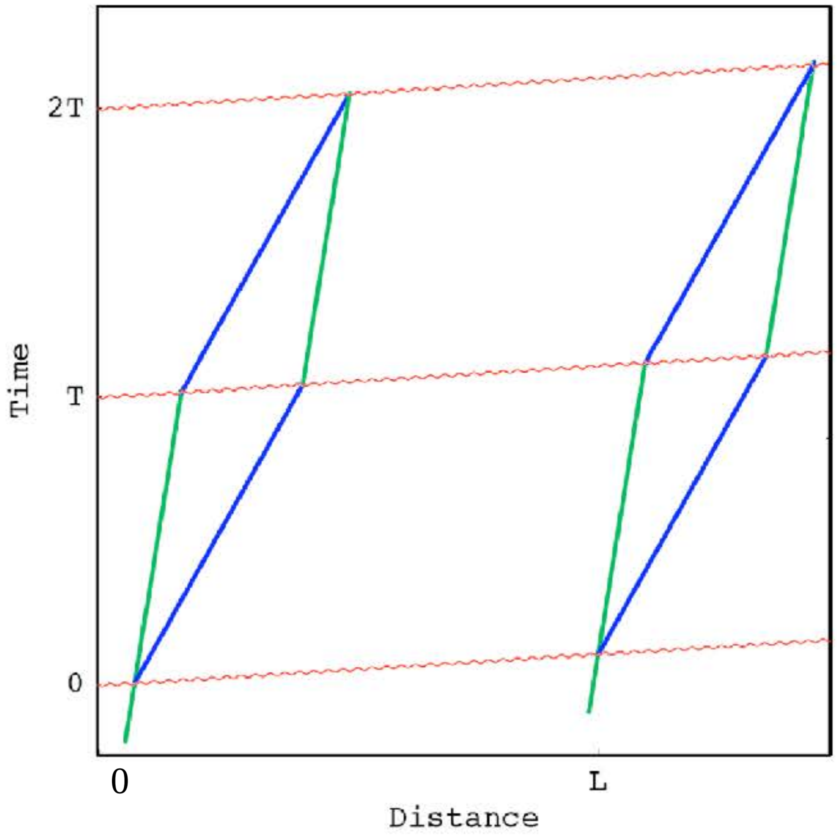


$$|0\,\hbar\mathbf{k}\rangle \xrightarrow{\text{LMT}} |2N\hbar\mathbf{k}\rangle\, e^{iN\phi_L}$$

→ Phase amplification factor *N*

Differential Measurement

Run two, widely separated atom interferometers using common lasers.



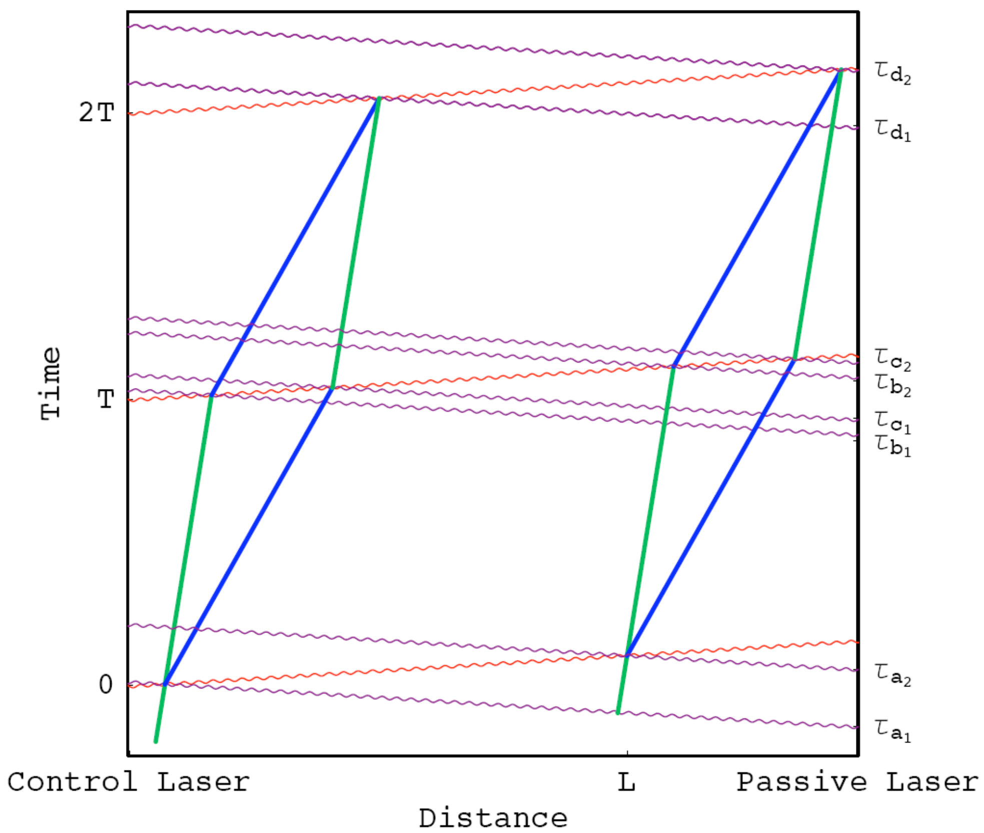
Measure differential phase shift between the two interferometers.

Gravitational wave signal is retained in the differential phase shift ~ $k_{\text{eff}}\, hL$

Laser vibration and phase noise cancels (up to finite light travel time effects).

Differential Measurement

Run two, widely separated atom interferometers using common lasers.



Light from the second laser is not exactly common

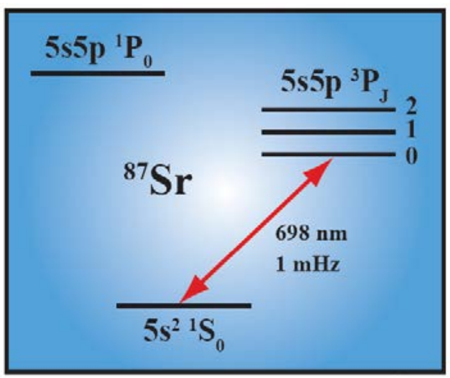
→Light travel time delay is a source of noise

→Single photon transitions avoid this problem

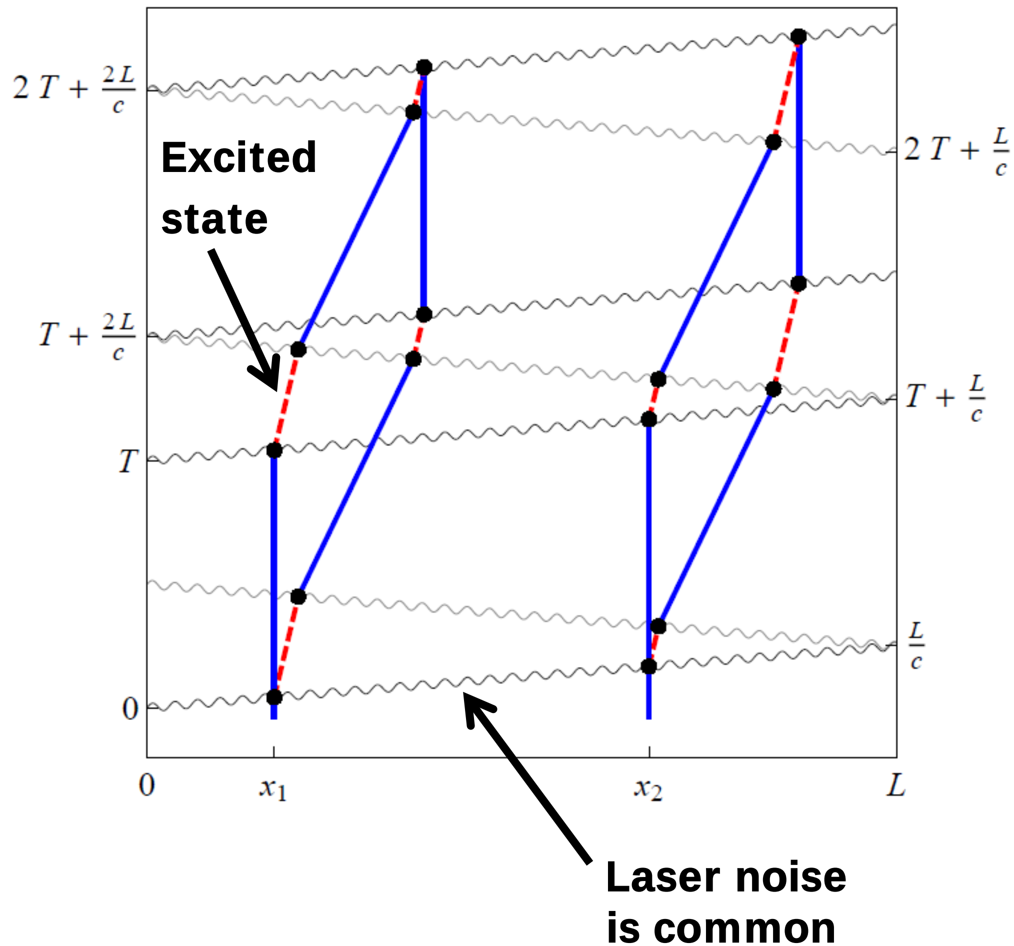
Laser frequency noise insensitive detector

All previous interferometric GW detectors need multiple baselines or ultra stable lasers.

- Long-lived **single photon** transitions (e.g. clock transition in Sr, Ca, Yb, etc.)
- Atoms act as clocks, measuring the light travel time across the baseline (time in excited state).
- GWs modulate the laser ranging distance.



Clock transition in candidate atom ^{87}Sr



arXiv:1206.0818

LMT with single photon transitions

GW Phase Shift in the Atom Interferometer

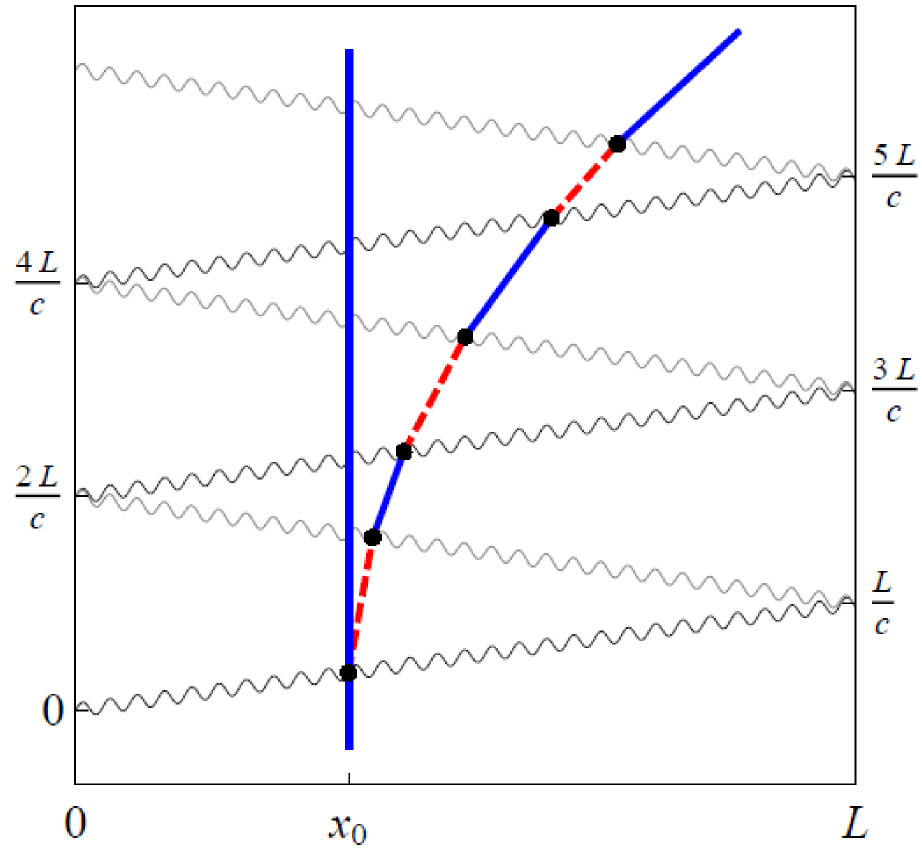
$$\Delta\phi = \frac{4N\omega_a h}{c}(x_1 - x_2)\sin^2\left(\frac{\omega T}{2}\right)\sin(\phi_0 + \omega T)$$

Atomic level splitting (optical)

GW ph

- Interesting sensitivity requires Large Momentum Transfer (LMT) atom optics (large N).
- LMT realized by sequential pulses from alternating directions.
- Selectively accelerate one arm with a series of pulses

Example LMT beamsplitter (N = 3)



Reduced Noise Sensitivity

Intrinsic laser noise cancels. What are the remaining sources of noise?

Any **relative velocity** Δv between the interferometers affects the time spent in the excited state, leading to a differential phase shift.

Leading order kinematic noise sources:

1. Platform acceleration noise δa

2. Pulse timing jitter δT

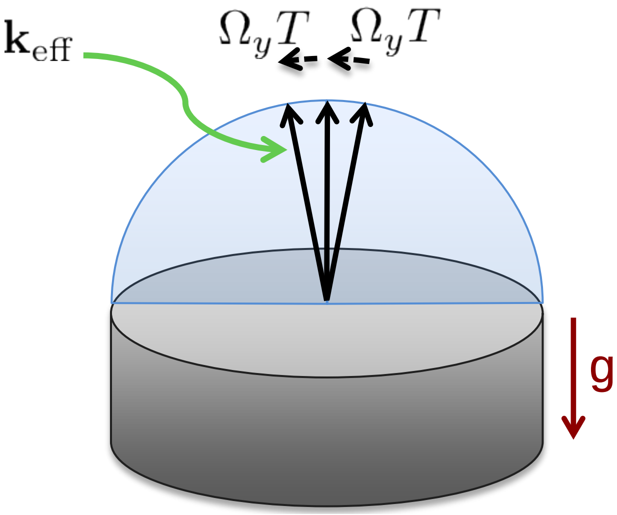
3. Finite duration $\Delta\tau$ of laser pulses

4. Laser frequency jitter δk

	Phase Shift	Control Required
1.	$N\frac{\Delta v}{c}\frac{\omega_a}{c}T^2\delta a$	$\delta a \lesssim 10^{-8} g/\sqrt{\text{Hz}}$
2.	$N\frac{\Delta v}{c}\omega_a \delta T$	$\delta T \lesssim 10^{-12}$ s
3.	$N\Delta v\,\delta k\,\Delta\tau$	$c\delta k/2\pi \lesssim 10^2$ kHz$/\sqrt{\text{Hz}}$
4.	$N^2\frac{\Delta v}{c}\frac{\hbar}{m}\frac{\omega_a}{c}T\delta k$	$c\delta k/2\pi \lesssim$ GHz$/\sqrt{\text{Hz}}$

Differential phase shifts (kinematic noise) suppressed by $\Delta v/c < 3\times10^{-11}$

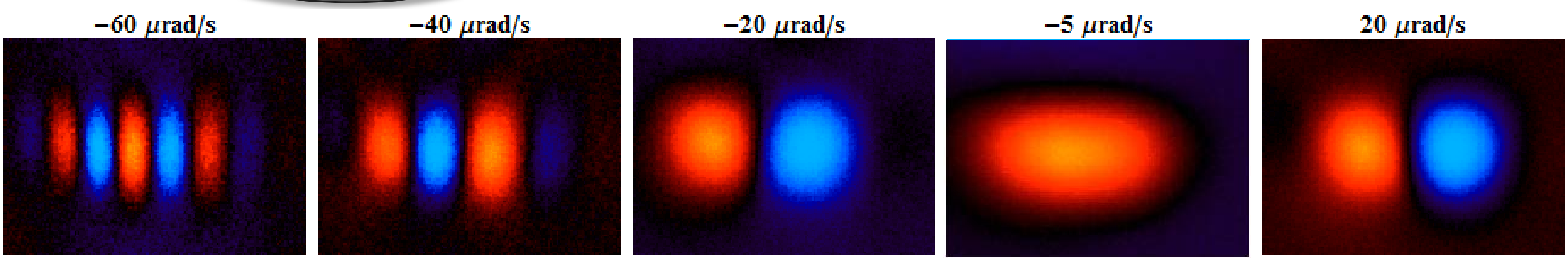
Compensating for Coriolis



Residual Coriolis phase: $\Delta\phi_\perp = 2k_{\mathrm{eff}} v_x T^2 \Omega_y$

Point Source Interferometry (PSI):

- Cloud expands much larger than initial size
- Image shows velocity-dependent phase shifts



Coriolis phase vs. rotation rate offset (Nominal Earth rate: 57.9 μrad/s)